SIMULATION BASED DESIGN AS AN ENABLER FOR CONDITION-BASED-MAINTENANCE AND TOTAL OWNERSHIP COST REDUCTION FOR UNDERSEA VEHICLES

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Abstract

Much has been written on the cost advantages of Condition-Based-Maintenance (CBM) when compared to a Scheduled Maintenance protocol. This paper presents an argument that CBM is not only mandated on a cost basis, but can be justified on a technical basis as a necessity for future Navy undersea weapon systems. Navy undersea weapon systems are characterized by long service lives that are measured in decades and new systems typically differ radically from those they replace. For these new, technologically advanced systems, the lack of design similitude with prior systems makes robust scheduled maintenance impossible. We propose that the technical foundation and required tools to develop a robust system CBM plan for both new and legacy systems are resident in Simulation Based Design (SBD) environments such as that currently under development within the Office of Naval Research (ONR) Undersea Weapon Design and Optimization (UWDO) initiative. Through the utilization of SBD methodologies, a CBM maintenance strategy can be developed concurrently with other vehicle design requirements, leveraging much of the system's organic data network for system monitoring, diagnostics and maintenance cueing. This framework can then be utilized as the foundation for the development of in-flight self-health monitoring and self-help capabilities that increase the overall likelihood of mission success. An example is shown highlighting the synergy between an active-control torpedo silencing system and Condition Based Maintenance.

Key Words: Conditioned based maintenance; Cost reduction; Design simulation; Machinery monitoring; Torpedo; UUV

Introduction: Naval weapon systems, and torpedoes in particular, present some unique design challenges. Recent years have seen dramatic increases in both the proliferation and sophistication of worldwide undersea warfare threats, calling for improved weapon performance capabilities and the deployment of new systems to support both offensive and counter-weapon scenarios. However, declining budgets demand delivery of this increase in performance and availability at a lower cost.

Domestically, a major portion of the Navy's budget for undersea weaponry is committed to ownership costs. Within the current infrastructure, weapon system readiness and crew readiness are competing constraints from a budgeting viewpoint, that both affect system performance. The current Navy torpedo weapon systems are periodically exercised to ensure proper operational readiness of the weapon system, platform and ships crews. Following each exercise the entire weapon is recovered, disassembled, critical components are replaced, and the vehicle is reassembled. In addition, a significant portion of the weapon inventory remains in storage for extended periods of time. In order to ensure the operational readiness of those vehicles in storage, they are also routinely disassembled and refurbished. This process, which is costly in terms of both system availability and dollars, is required for the current torpedo weapon systems due to their harsh operating environments and stringent performance and reliability specifications.

New technology is introduced to our Fleet by two means, either as a series of focused upgrades of existing "legacy" systems, or bundled into a new replacement weapon system. The current Fleet torpedo design is a product of the former route. Based to a great extent on a design introduced thirty years ago, it has evolved through significant upgrades in sensors, signal processing, and propulsion. However, it's maintenance schedules appear to still demand a cold-war budget.

Based on a throughput study conducted by the Navy [1], the current heavyweight torpedo requires 83.2 manhours to be turned around, i.e. take a weapon recovered from the exercise range and refurbish it for the next firing. Figure 1 depicts a procedural flow chart where every square block represents a set of step-by-step instructions on how to refurbish every component of the system. The Navy maintains an exercise-firing rate of approximately 650 units per year. Using a standardized labor rate of $65 per hour and a 30% overhead charge, it costs over $ 4.5 million per year in labor to perform the scheduled maintenance cycle on one the Navy’s torpedo systems. In addition, the average yearly cost of “As Required” and “Mandatory” replacement parts used in this turnaround process is $2.4 million. Along with a $1.8 million per year cost associated with the hazardous waste stream generated during the torpedo turnaround cycle, the yearly cost of scheduled maintenance is approximately $8.7 million.

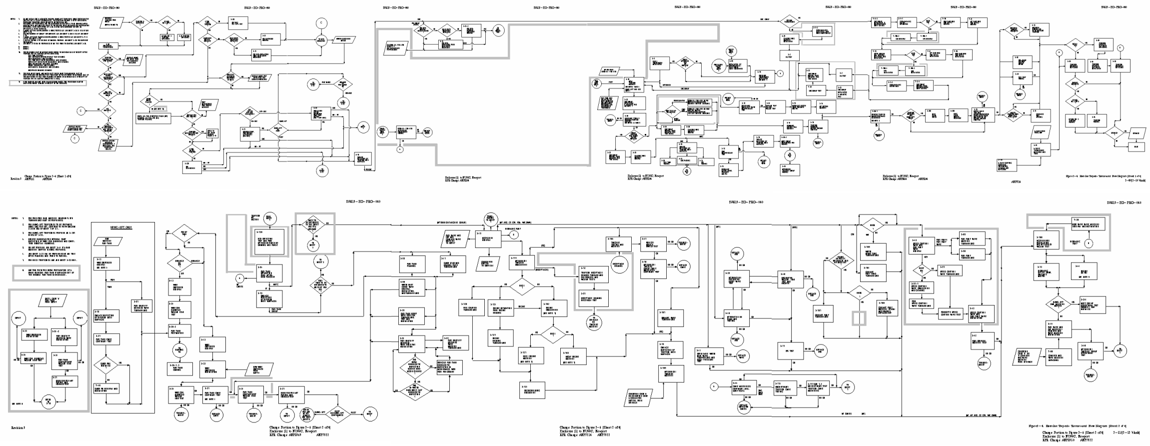

Figure 1. Navy Torpedo turnaround flow diagram

With continuous upgrades to the weapon system originally introduced in the late 1960’s, the turnaround process has remained remarkably stagnant. Very few turnaround procedures are eliminated as a weapon system becomes more advanced. Typically more advanced procedures and equipment are required to support technology improvements, continuously increasing the complexity and cost of the scheduled maintenance cycle.

Some improvements have been proposed for cost reduction in the present torpedo maintenance scenario. These include the introduction of less corrosive fuels and the replacement of thermal power plants with electric or thermal-electric hybrid propulsion systems. These alternatives alone will not solve the current scheduled maintenance problem. At present, our best-practice maintenance strategies are those where diagnostics are easily performed, such as in the vehicle's signal processors. In these instances our screening is still limited to diagnostic, not prognostic capability. In the mechanical and propulsion sub-systems it is not possible to thoroughly assess system status without a complete disassembly.

In contrast, the Navy's ship and submarine communities have adopted a more proactive maintenance philosophy, which is a form of CBM [2]. Because these systems are under continuous duty, operating conditions may be monitored with the appropriate sensors, and CBM adjustments made to the time-based maintenance schedule. Some Navy Unmanned Undersea Vehicle (UUV) projects also use this strategy. However, for the weapon community, with a largely idle inventory, this model is not practical. Given the standing inventory, and lack of integral sensing capability, scheduled maintenance is the only option for assured availability of the existing systems.

As we strive to bring the most promising technologies forward in all areas such as sensors, signal processing, propulsion and structures, we will no longer be able to develop or afford a time-based maintenance strategy. For many of the technologies being developed there is insufficient operational data for an inference model of reliability. Our assertion is that robust performance in next-generation systems will require condition-based maintenance protocols wherein the system itself is equipped with sensors and the processing capability to provide thorough self-condition diagnostics. Furthermore, these diagnostic systems should be integrated with platform and on-board mission planning systems. In this way, a prognostic capability is created which can optimize the mission tactics for the actual weapon performance in real time. We now suggest that the basis for both the CBM and real-time mission prognostic capability exists in Simulation Based Design (SBD) environments where the new vehicle technologies are being developed.

Simulation Based Design Environment Overview: Next-generation torpedo, counter-weapon and UUV technology development efforts focus on those few, revolutionary systems that provide wide-ranging strategic advantage. The Undersea Weaponry Design and Optimization (UWDO) project (Figure 2) was established by the Office of Naval Research (ONR) to provide system design capability for this scenario, one in which new and diverse technologies are rapidly brought to maturity, integrated and deployed. The simulation based design environment of UWDO provides a collaborative architecture for creation, simulation, and optimization of these technologically advanced systems.

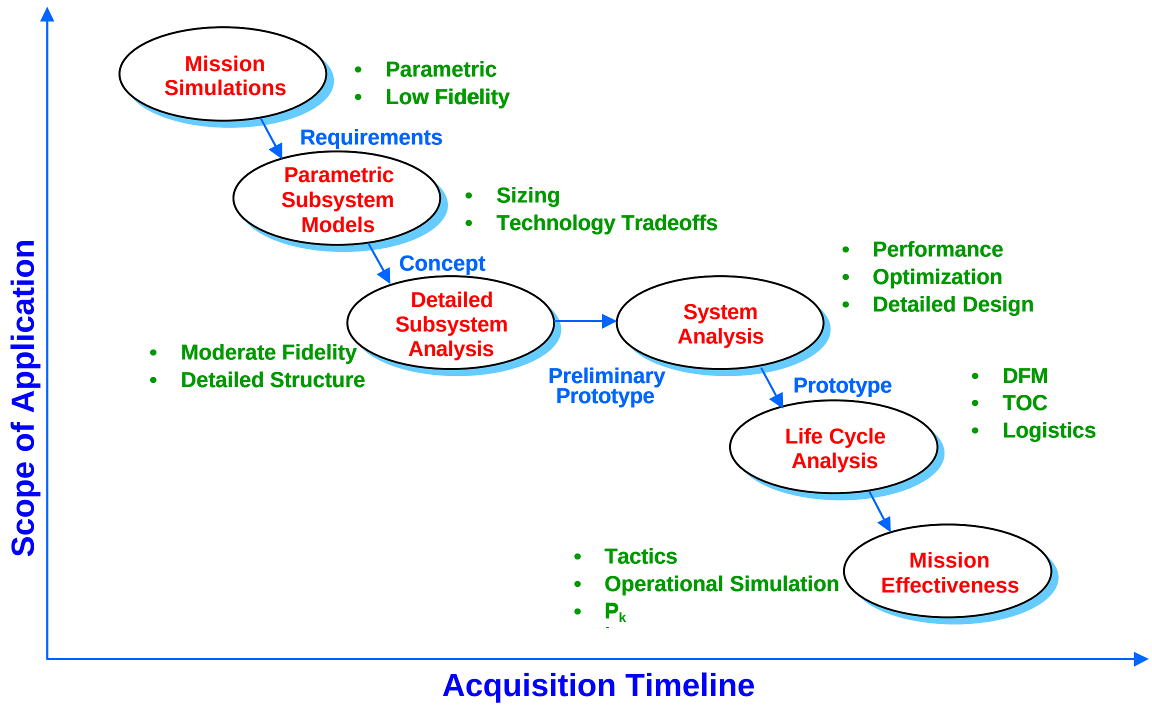

Figure 2: SBD/UWDO Process overview

For the innovative system developed within the UWDO environment, the relevant information for the condition assessment and maintenance plan is resident in that system's SBD database. Information gathering and widespread information exchange are fundamental tenets of the UWDO approach. Each component is represented analytically in the product data model, including physical and logical interfaces. The components and sub-systems are linked by a network architecture in the simulation, which is again mirrored in the sensing, signal processing and control systems in the actual vehicle payload, propulsion and guidance systems. Our challenge then, is to exploit the inherent sensing and flow of parametric information in order to provide diagnostic, and in-flight prognostic condition assessment.

SBD Example of Next-Generation Torpedo: The Navy's increasing need for enhanced weapon performance is driving torpedo development in the direction of smaller weapons with broader mission envelopes. This will increase the number of weapons per submarine loadout and allow for their use in a wide variety of tactical situations. If one weapon system can be developed that meets the requirements of the existing systems, the facilities and infrastructure associated with multiple obsolete weapon systems could be eliminated and a substantial cost savings will be realized. This next generation multi-mission weapon must leverage SBD methods to reduce Life Cycle Cost (LCC) as well as development and acquisition costs. Thus, the Total Ownership Costs (TOC), which is the sum of all the costs associated with the development, acquisition, deployment and disposal of a weapon system, could be significantly reduced through the development of technologically advanced Next-Generation undersea weapon systems.

Total Ownership Cost reductions could also be affected through an enhanced capability for rapid mission reconfiguration and vehicle turnaround. This implies a need to anticipate the costs and process flows for assembly and re-assembly of a modular product. While mission reconfiguration will be dominated by software requirements, rapid turnaround will require plug and play components and enhanced system self-diagnostic capabilities. These self-diagnostic features will support a Condition Based Maintenance process that results in reduced expenditure of spare parts, consistently high performance and rapid redeployment.

Product Model Development**:** In order to enable the timely development of technologically advanced and highly effective undersea weapon systems, simulation-based trade studies and performance assessments must be conducted prior to prototype fabrication. The SBD design process begins with the creation of an analytical system network, linking components into sub-system and system-level performance models. Components, including structures, circuits and harnesses are integrated in a three-dimensional solid model of the physical system (Figure 3). Each component has associated with it a set of material constitutive properties or circuit parameters, assembly interface and constraint information, and operational, load and motion specifications. This model is used to perform physics based analysis of individual components, ensure proper fitment and assembly of the system, and to develop a manufacturing documentation package. The model is also linked to simulations that evaluate mission effectiveness and provide for tradeoffs of complexity versus value. These simulations provide significant cost and schedule benefits by minimizing hardware prototyping, and supporting in-service operations. In conjunction with this analysis, Design for Assembly, Design for Service and Environment software and other tools are used to develop a design with significantly reduced TOC. Failure modes and effects analysis modeling is also conducted for performance troubleshooting and to identify maintenance and wear issues.

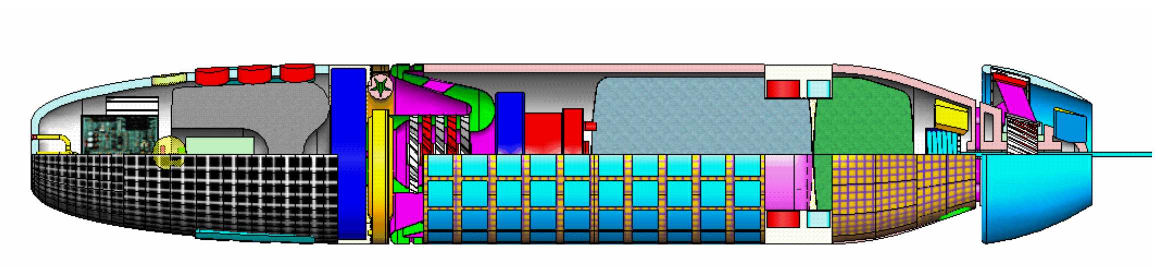

Figure 3. Solid model of next generation torpedo

Performance Evaluation Through Simulation: The conceptual next generation torpedo shown is small in size to reduce its required storage space, contains advanced conformal arrays to increase its sonar sensing capabilities, and is powered by a hybrid thermal-electric propulsion system with an integrated motor propulsor to maintain performance over a wide mission envelope while maintaining vehicle stealth.

Featureless noise signatures greatly increase the effectiveness of undersea weapon systems. Thus, the reduction of radiated noise for undersea vehicles is always a major requirement in their development. The simulation-based environment can predict vehicle performance parameters and radiated noise signatures using the solid model of the system in conjunction with kinematic, electromagnetic, thermodynamic and acoustic models (Figure 4). These tools can be used to perform a high fidelity assessment of mechanical and operational performance in a fraction of the time it would take to evaluate the system through an actual test program. The mechanical and acoustic performance parameters are ultimately applied to drive mission effectiveness simulations that provide the final technical evaluation based on increased probability of kill versus the cost impact of new technology insertion. These simulations will also provide the metrics for evaluating the impact of performance degradation to determine allowable wear for a CBM implementation.

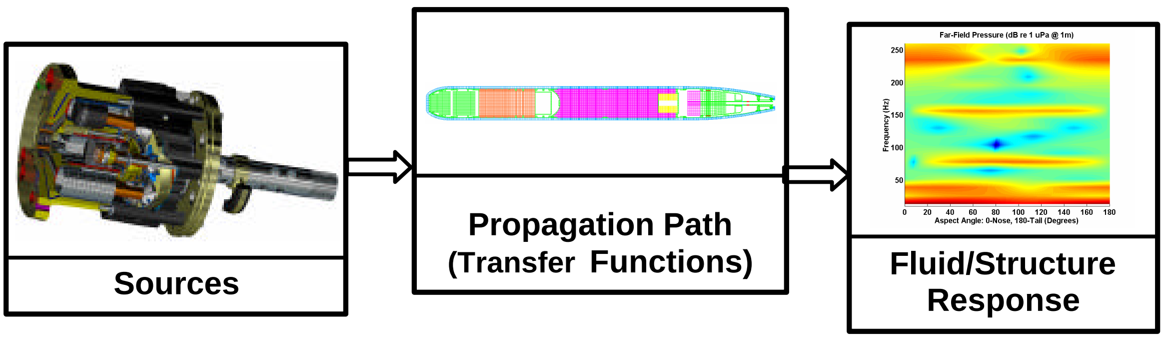

Figure 4. Results from integrated solid, thermal, and acoustic models

<u>System Maintenance and TOC Reduction:</u> Within the simulation environment, the solid model vibration predictions of system components can be used to statistically predict critical component life to failure. Ordering components by how likely they are to fail, and how critical they are to the successful operation of the weapon, a condition based maintenance plan can be developed to monitor the components most likely to prevent the weapon from completing its mission. A condition based maintenance plan is critical to reducing the Total Ownership Cost of undersea weapon system.

<u>Transition to Condition-Based-Maintenance:</u> As acquisition timelines contract in response to emerging military threats and changing operational requirements, the Navy will be continuously developing and deploying systems with multiple innovative elements that are without historical precedence. Yet, it remains essential that these new systems be robust in-theater. Under a traditional Scheduled Maintenance (SM) system, component life must be understood, accurately modeled, and maintenance strategies developed to ensure robust system performance. In making the transition from SM to CBM, we allow a relaxation of the time-based maintenance schedules in favor of using appropriate sensing systems. The goal is to achieve in real-time, a thorough knowledge of actual equipment condition with respect to the acceptable design limits. For complex systems such as torpedoes and UUV's, both static and dynamic variables are under consideration. To measure those parameters that are necessary for a robust condition assessment, system design simulations shall be utilized to facilitate identification of critical components and the design and placement of appropriate sensors.

To summarize, SBD provides an environment to forecast system performance, and the full range of life cycle costs, before committing to prototype production. Total Ownership Cost and, thus, overall system affordability is determined by the decisions made in the design phase. Using the SBD approach, an information-based, multi-objective optimization capability can be utilized to minimize the operational and maintenance costs required to achieve the desired levels of performance.

Synergistic Active Noise Control / Condition Based Maintenance System: In order to maximize the effectiveness of a condition based maintenance plan, it may be possible to utilize existing components in the system as monitoring sensors or indicators of required maintenance. This concept would save the costs required to integrate a stand-alone monitoring system into the vehicle. One system that may have the potential to be used for both active noise control and a condition monitor is an active noise control device mounted on the weapon's drive shaft.

To illustrate how an SBD approach can be utilized to develop a synergistic active noise control and conditioned based maintenance instrumentation suite, a case study design of a tactical scale, undersea weapon, drive shaft bearing package will be presented. The study will show how active noise control sensors previously integrated into the design to eliminate problematic bearing noise can be used as a diagnostic tool to monitor bearing performance prior to an in-water run, and determine when the bearings are to be replaced. This is a major change to the historical maintenance philosophy in the Fleet, where full post run turnarounds and part replacement has been the standard. This approach will not only save the cost of unnecessary part replacement and labor, but by determining the system performance prior to deployment will ensure that reduced maintenance does not increase risk of failure.

<u>Active Noise Control System</u>: Discrete tones radiated into the water by an undersea vehicle are very distinctive and can compromise weapon location and identity for the target. Particularly problematic are tones produced by fluctuating forces on the propulsor and radiated by the vehicle hulls. Determination of the system's dynamic response provides the identification of structural modes that may transmit acoustic energy. Structural acoustics models can then identify which of these modes are efficient radiators. In order to interrupt the transmission path of these vibrations from the propulsor to the shells, passive isolation can be added around the bearing housing that holds the output shaft. To improve the performance of the passive isolation, which is usually limited in its performance by alignment capability, an active vibration control system can be implemented (Figure 5).

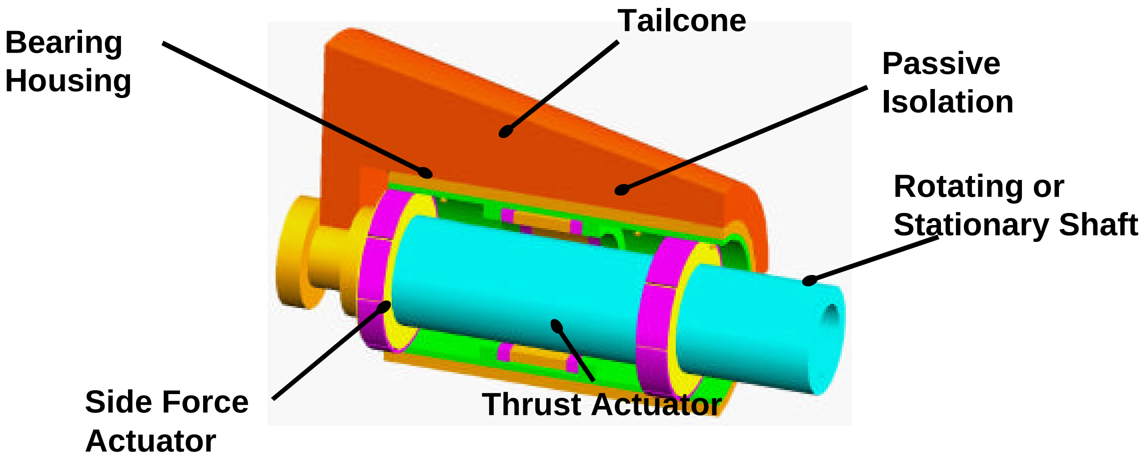

Figure 5. Active Noise Control System for Output Shaft Bearing Package

The system shown would include axial and radial accelerometers to measure shaft vibration levels and phase. With the vibration information, the side force and thrust actuators can be operated in an opposite phase to the shaft vibration lowering the overall vibration levels transmitted into the shell structure, and subsequently into the water. Typically active noise control systems that are currently in use can dramatically reduced the narrow band signature from a bearing housing package. (Figure 6)

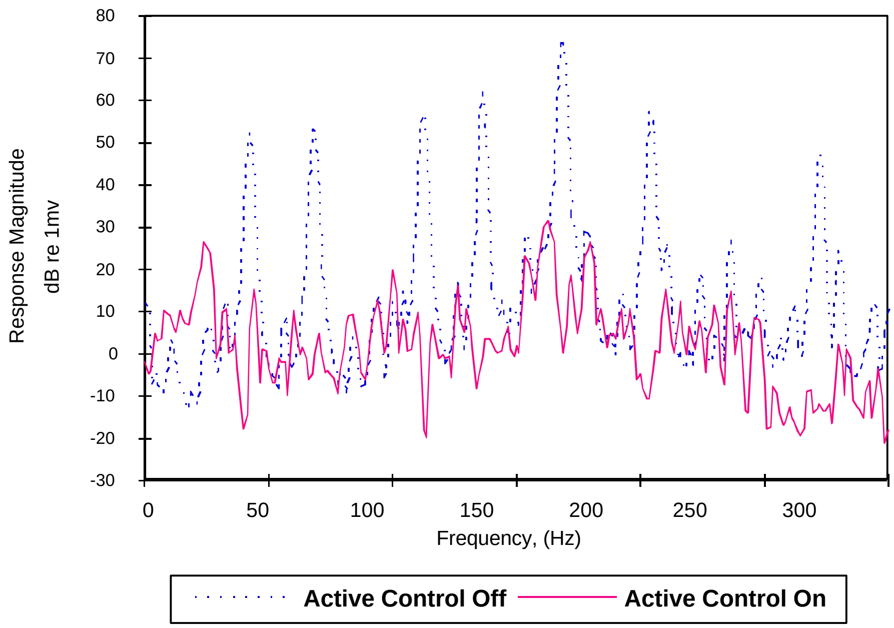

Figure 6: Active control system reduction in narrowband tonal excitation at bearing housing

Condition Based Maintenance Plan for Shaft Bearings: Along with the propulsor vibrations present on the output shaft of the vehicle, the bearings used to hold the shaft in position can become a vibration sources if defective. These vibrations, whose frequencies are a function of shaft RPM and the type of defect present, can be observed in radiated noise measurements as they increase in amplitude. Eventually bearing failure may result. Specific bearing defects, such as a ball or an inner race defect, would produce a single tone in the radiated noise. Overall bearing wear will result in a broadband increase in the entire signature. Figure 7 shows a vibration spectrum for both good and defective bearings.

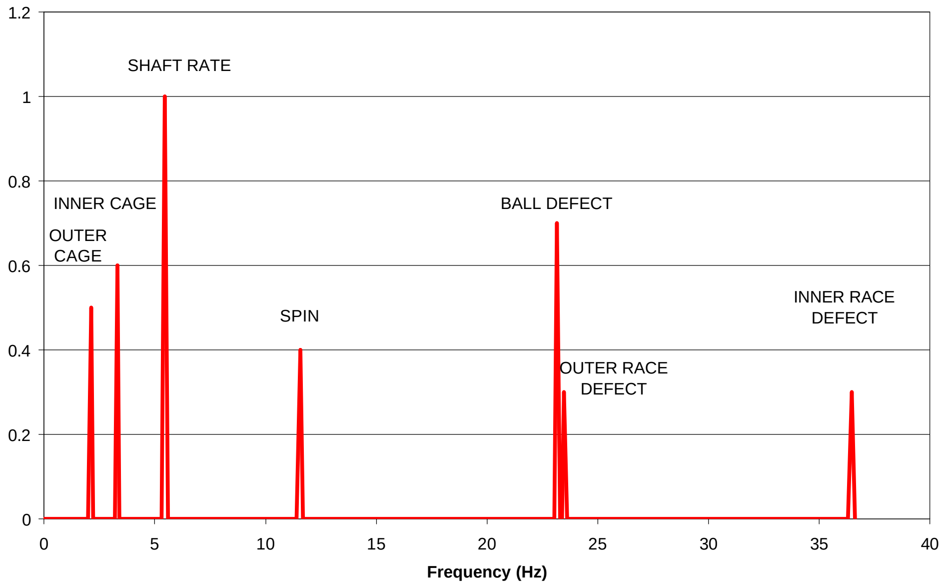

Figure 7a. Example Narrowband Spectra of Ball Bearing Defects

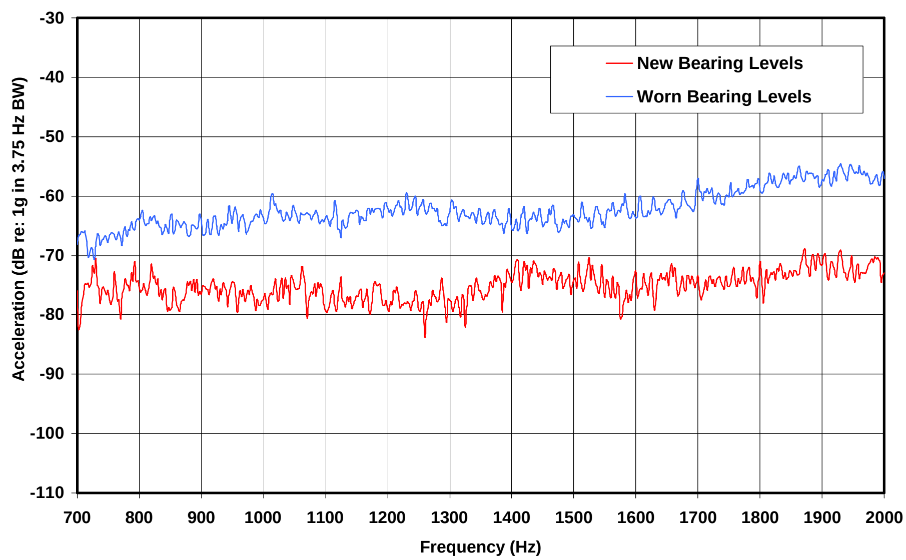

Figure 7b. Broadband Vibration spectrum of good and defective bearings

If this were an existing weapon there would be no mechanism in place to measure the bearing vibrations during the vehicle turnaround, so the bearings would be replaced each time regardless of condition. However, in the next generation weapon, there would already be an active noise control system in place on the bearing housing with integrated accelerometers. These instruments could be used to measure bearing vibration prior to an exercise as part of a condition based maintenance program. Either the internal electric drive motor, or an external motor could be used to spin the shafting of the vehicle while undergoing pre run checks. The vibration data from the integrated accelerometers could be monitored for specific tones, or overall level increases. If the increases were larger than a predetermined limit the bearings would be replaced. This methodology of replacing parts on an as needed basis would greatly reduce the current recurring labor and procurement costs associated with global part replacement following each weapon exercise.

Ultimately this system will be self-monitoring to provide real time health information in-flight. A diagnostic signal could be used in a neural-net comparator to trigger prognostic algorithms. Increases in broadband noise could be attributed to wear or seal leakage. Increases in narrowband tonals could be attributed to bearing defects. The processor, analyzing the severity and rate of increase in the signals, could determine corrective action, either increasing narrowband noise suppression or decreasing speed to reduce bearing load, to improve the likelihood of completing the mission. For exercise runs, the vehicle data record would contain adequate information for end of run assessments of bearing condition, possibly saving teardown and turnaround cost.

Total Cost Ownership (TOC) Reduction: An SBD approach can be utilized to effectively reduce the developmental costs of a new weapon system by eliminating the need for costly cycles of prototype design and fabrication. Simulated parametric studies can also reduce the need for costly performance evaluation test series and prototype system modifications. Both of these steps work to reduce the system development costs. To lower life cycle and maintenance costs, a SBD approach can be used to pin point problematic components and to estimate life to failure. To use this data in a Condition Based Maintenance program, the “intelligent” nature of advanced technologies can be utilized as a component monitoring system. Integrated sensors needed to implement advanced silencing and propulsion technologies can be used to monitor component output, such as bearing vibration, prior to an exercise to indicate the components condition and need for replacement. Eventually it may be possible to monitor component performance during the actual exercise, and eliminate the need to run separate diagnostic testing altogether.

Potential for Neural Networks in CBM: We see neural net processing as a potential complement to simulation in the development of robust next-generation systems. In the next generation torpedo and UUV systems postulated above, where comprehensive, statistically robust performance models may not yet exist, a neural net approach has great appeal. One of the better-known applications of neural networks is in pattern recognition. Properly executed, a neural net “maintenance manager” can provide vital function diagnostics in the absence of a comprehensive set of expert rules or system models. The Air Force [3] and NASA [4] have begun to show the potential of neural net processing to learn system behavior, and when combined with Bayesian probability classifiers, to identify likely faults during depot testing. Such an approach can accelerate the transition to a conditioned-based maintenance protocol for the undersea vehicle community. Given adequate sensing and system topology models, CBM can be enabled earlier, as all run data becomes processor-training data. Again, using neural nets, comprehensive system performance models are not required. We also see great potential for using this approach for in-flight vehicle processing. When incorporated in the post-launch processing of these vehicles, a neural-net diagnostics system can feed potential prognostic algorithms for in-flight mission planning. In the event of an in-flight fault, such a system could determine an optimal degraded mode of performance to continue execution of mission objectives. Many examples can be envisioned; such as solving rotor-dynamics problems, where the controller can learn to avoid critical speeds; or in sonar optimization, where modifications can be prescribed in-flight, altering beam-forming or signal processing to account for a faulty transducer or drive components. These issues are particularly relevant to long duration, low observable missions such as those performed by a UUV or stealthy torpedo. For systems that exist as standing inventory, such as naval weapons, incorporation of neural net-based self-health monitoring appears to be essential for assured reliability.

Summary: Simply stated, system maintenance is performed to keep systems on-line or to ensure availability. Scheduled maintenance uses historical statistics on component or subassembly failure as a basis to prescribe service intervals. Where risk of failure is greater, maintenance intervals are shorter, and service costs are higher. The principal detractions of Scheduled Maintenance are the removal from service of a functioning system, and the costs of maintaining a distributed spares and service network. For new, technically innovative systems, the lack of valid, analogous historical database makes robust Scheduled Maintenance impossible, irregardless of budget. The Navy has successfully adopted a Condition Based Maintenance protocol on ship systems, which operate continuously, and can be subject to monitoring. In these instances, CBM has been used as an adjunct to scheduled maintenance, taking pro-active steps to service components nearing their design thresholds. For systems that run only occasionally and have extreme reliability requirements, such as torpedoes and UUVs, a new strategy is required to fully employ CBM. Robust simulation is needed to develop the system fault trees. These directed graphs then provide a basis to prescribe the appropriate sensing schemes for diagnostic systems. To make the transition from a diagnostic to a prognostic capability, the next generation undersea weapon system will need to play an active role in its own maintenance. We see neural net processing, coupled with inference engines based on the system topology, as a promising means to achieve true real-time condition based maintenance in the maintenance facility, and system self-help prognostic capability throughout the vehicle mission.

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